Supporting information

Honeycomb-like hollow carbon loaded ruthenium nanoparticles as high-performance HER electrocatalysts

Peng-Cheng Ji, Yang Teng, Hong-Cheng Li, Ming-Yun Guan, Hai-Lang Jia*

School of Chemistry and Chemical Engineering, Institute of Advanced Functional Materials for Energy, Annlysis and Testing Center of Jiangsu University of Technology, Jiangsu University of Technology, Changzhou 213001, P. R. China.

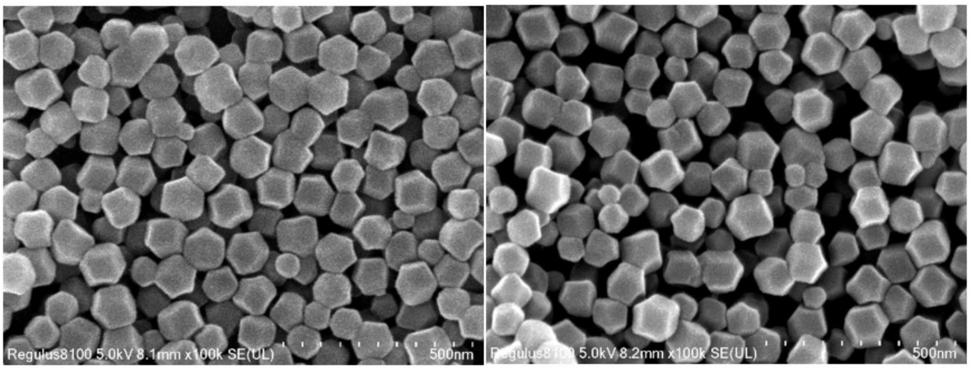

Fig. S1 SEM of ZIF8

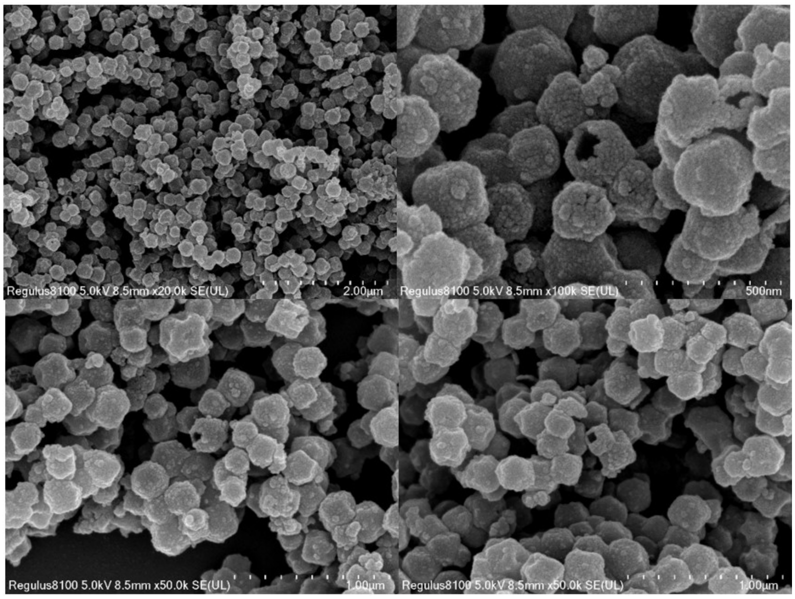

Fig. S2 SEM of ZIF8 obtained by direct etching

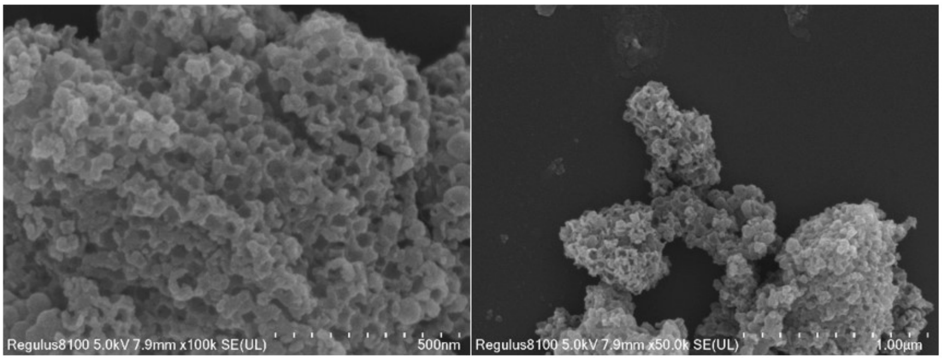

Fig. S3 SEM of H-ZIF8

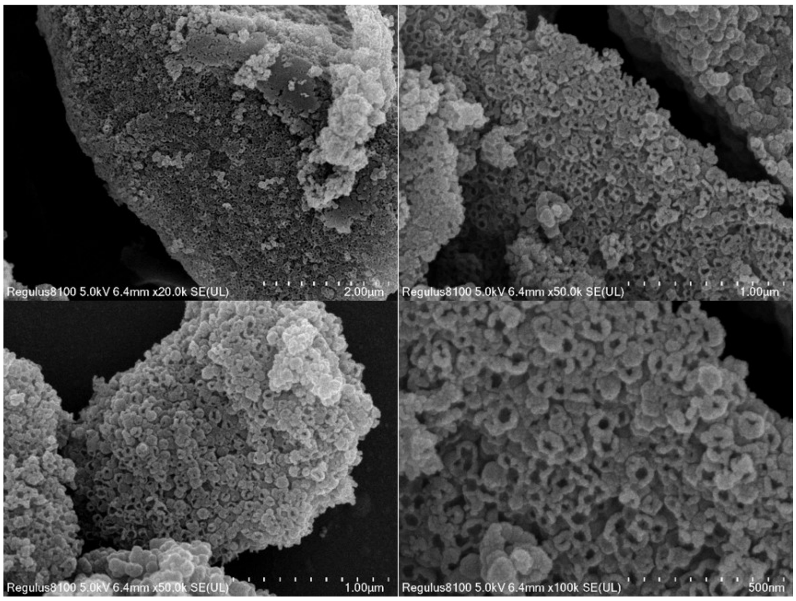

Fig. S4 SEM of Ru/HNC

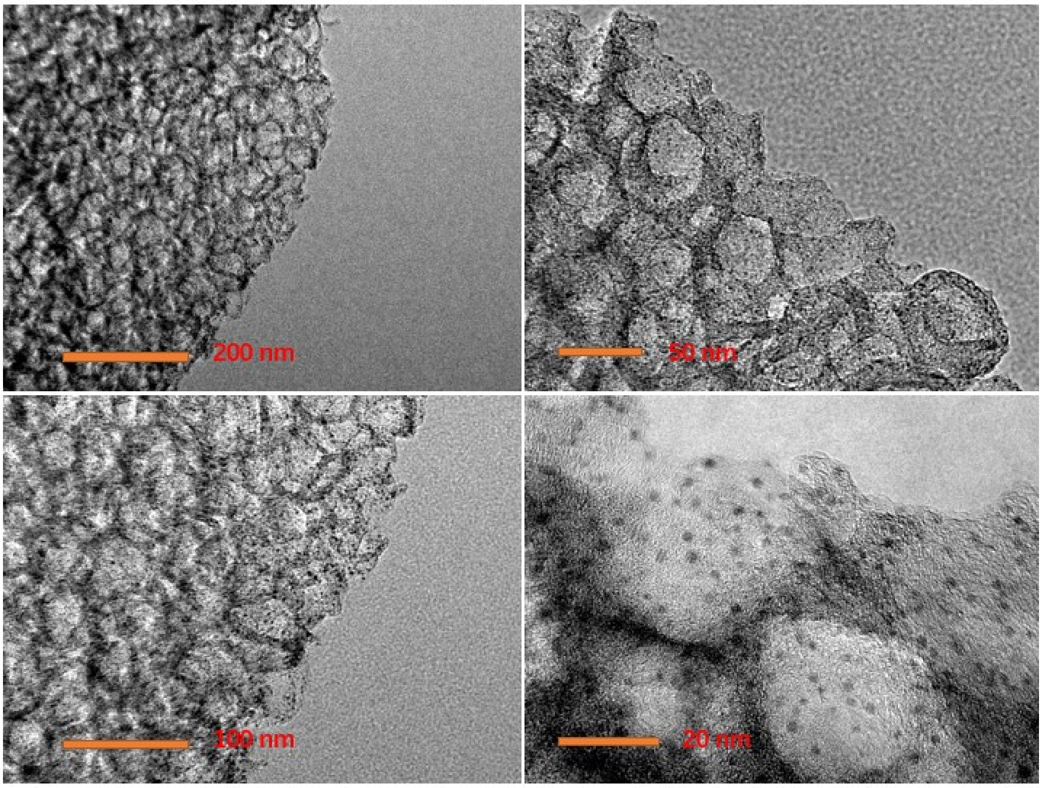

Fig. S5 TEM of Ru/HNC

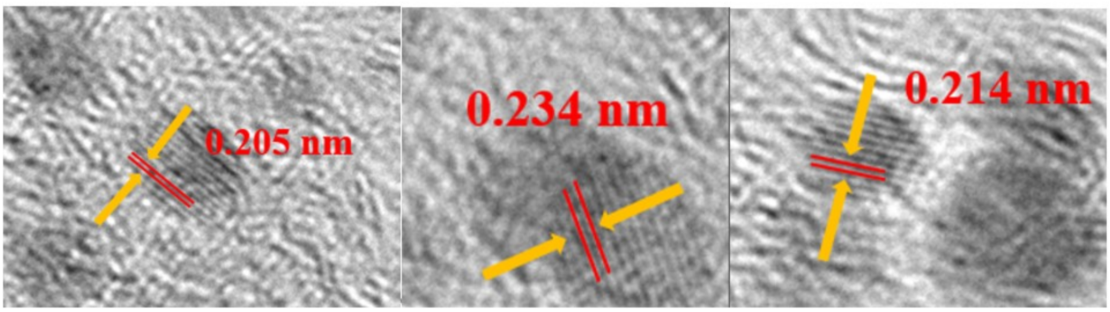

Fig. S6 HR-TEM of Ru/HNC

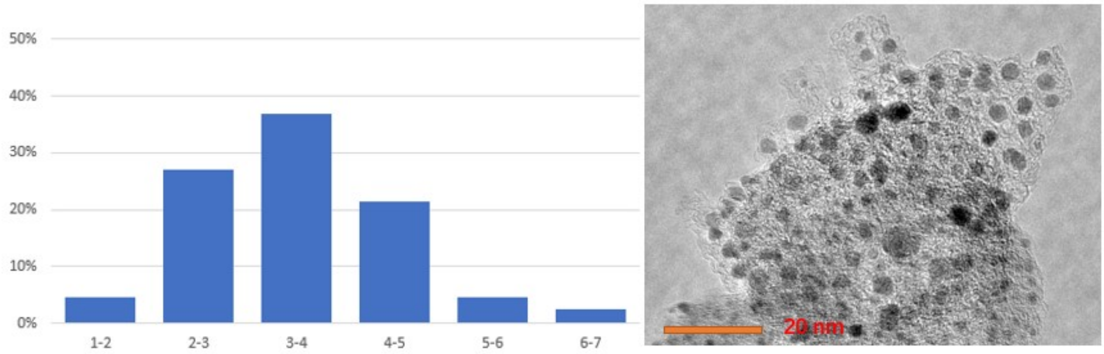

Fig. S7 Particle size distribution of Ru/HNC

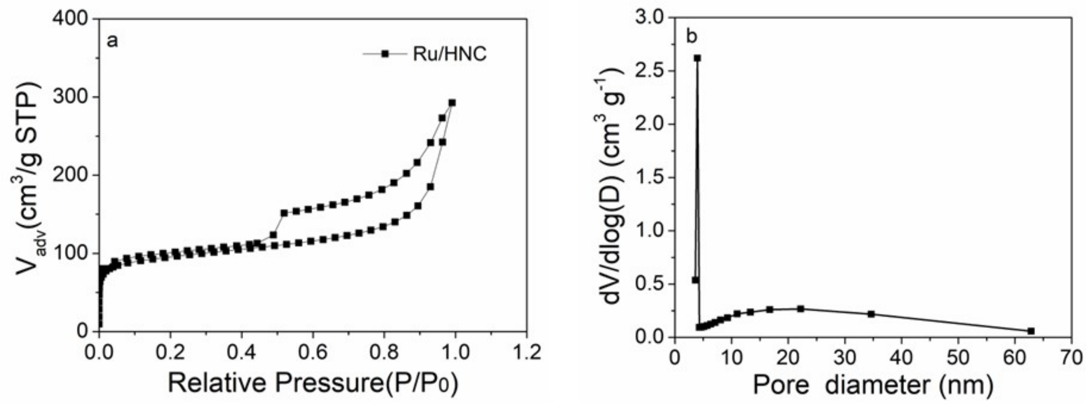

Fig. S8 (a) N_2 adsorption-desorption isotherms of Ru/HNC, (b) the pore size distribution of Ru/HNC.

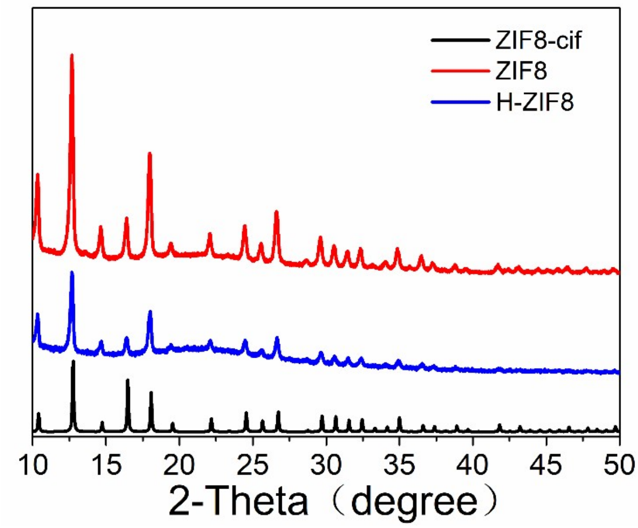

Fig. S9 XRD of ZIF8-cif, ZIF8 and H-ZIF8

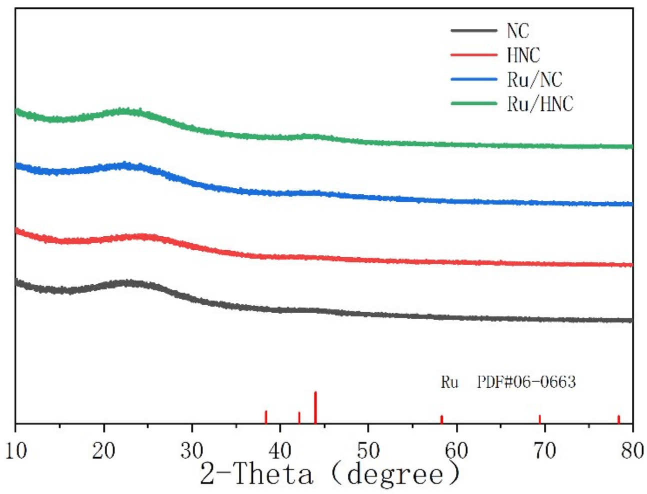

Fig. S10 XRD of NC, HNC, Ru/NC, Ru/HNC

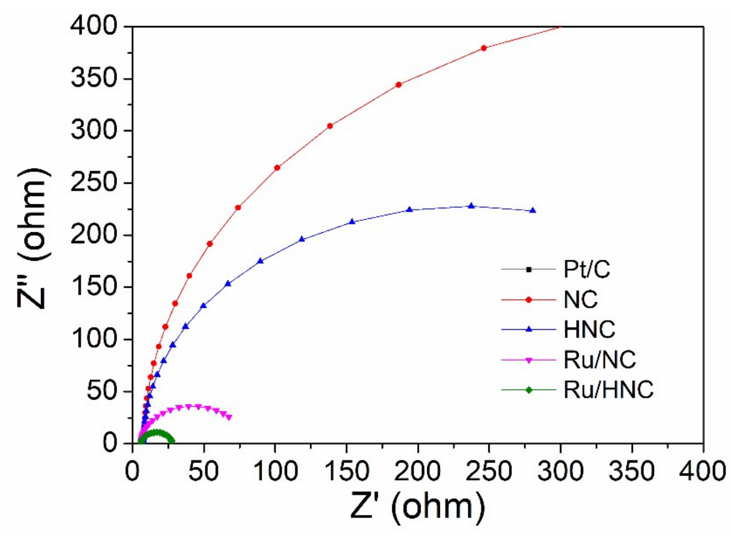

Fig. S11 EIS of NC, HNC, Ru/NC, Ru/HNC in 0.5 M H_2SO_4

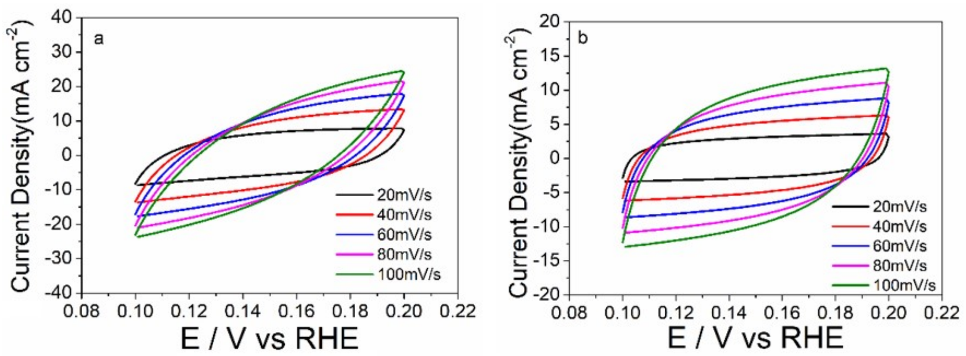

Fig. S12 CV curves of Ru/HNC (a) in 1 M KOH, (b) in 0.5 M H_2SO_4

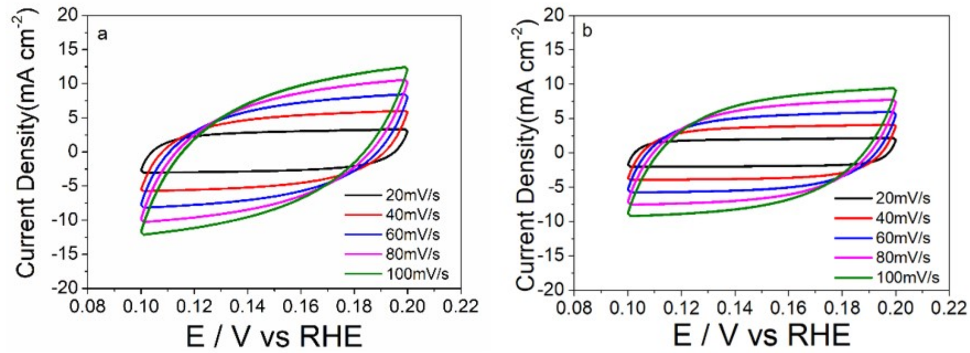

Fig. S13 CV curves of Ru/NC (a) in 1 M KOH, (b) in 0.5 M H_2SO_4

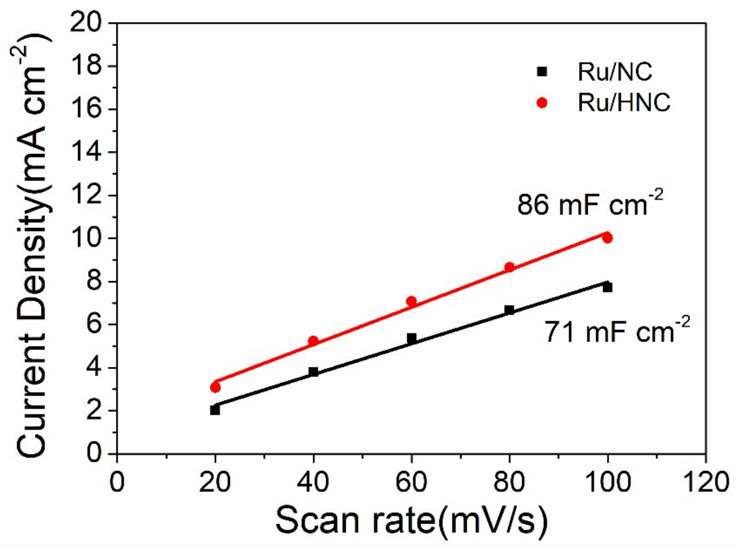

Fig. S14 The linear slope of Ru/NC and Ru/HNC, equivalent to twice the double-layer capacitance, Cdl was used to represent the rECSA in 0.5 M H_2SO_4

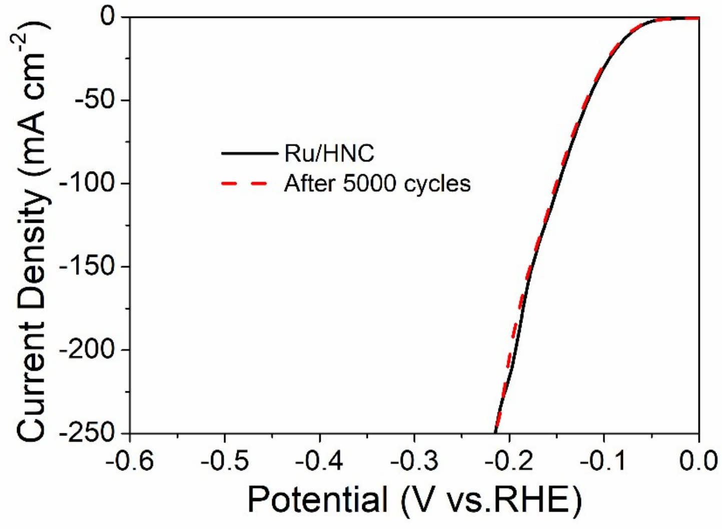

Fig. S15 LSVs of Ru/HNC catalysts before and after 5000 CV cycles in 0.5 M H_2SO_4

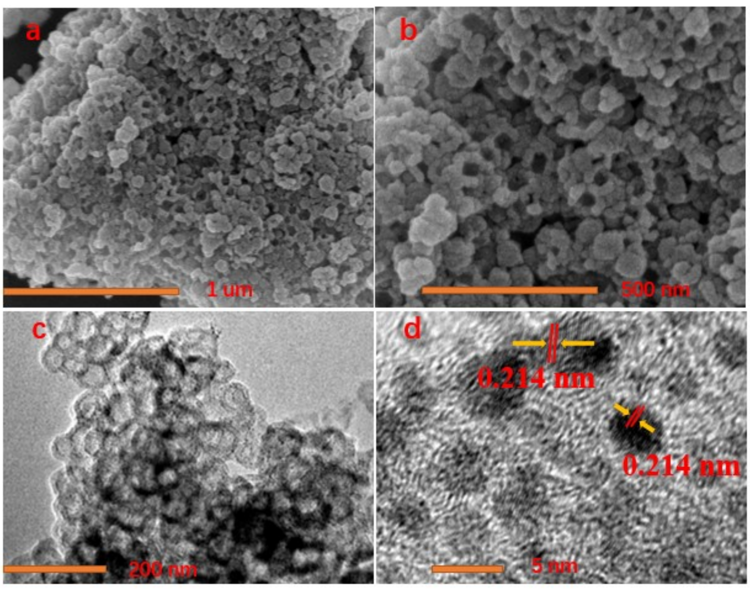

Fig. S16 SEM (a,b) and TEM (c,d) of Ru/HNC after 5000 CV cycles

Table S1. Summary of HER catalytic activities of Ru/HNC and some other catalysts reported in recent literatures (1 M KOH).

Catalysts	Overpotential	Tafel Slope (mV dec^{-1})	Ref.
Ru/HNC	44 mV at 10 mA cm^{-2}	72	In this work
Ru-CoP/NC	22 mV at 10 mA cm^{-2}	50	ACS Appl. Mater. Interfaces, 2021, 13, 56035−56044.
ld-Ru@a-Co/Ti	33.5 mV at 10 mA cm^{-2}	39.6	Chem. Commun., 2022, 58, 13588–13591.
Ni2P–Ru/NF	40 mV at 10 mA cm^{-2}	33.9	Sustainable Energy Fuels, 2023, 7, 2830–2840.
RuNP-RuSA@CFN-800	33 mV at 10 mA cm^{-2}	37.1	Adv. Funct. Mater. 2023, 33, 2213058
Ru/PEI-XC	13 mV at 10 mA cm^{-2}	79.3	J. Mater. Chem. A, 2021, 9, 22934–22942.
Ru/TiOxNy NBs	16 mV at 10 mA cm^{-2}	42	J. Mater. Chem. A, 2022, 10, 11205–11212.
Ru MNSs	24 mV at 10 mA cm^{-2}	33	Angew. Chem. Int. Ed. Engl., 2022, e202116867.
P-Ru-CoNi-LDH	29 mV at 10 mA cm^{-2}	69	Small, 2022, 18, e2104323.
CC@WS2/Ru-450	32.1 mV at 10 mA cm^{-2}	53.2	Adv. Funct. Mater., 2022, 2109439.
Ru-HMT-MP-7	33 mV at 10 mA cm^{-2}	26.4	Small, 2022, e2105168.
Ru-NiCo2S	32 mV at 10 mA cm^{-2}	41.3	Adv. Funct. Mater., 2021, 2109731.
Ru/P-TiO2	27 mV at 10 mA cm^{-2}	28.3	Angew. Chem. Int. Ed. 2022, 61, e202212196
Ru@NC	39 mV at 10 mA cm^{-2}	37.9	ACS Sustainable Chem. Eng. 2022, 10, 15530−15537
Ru@Co/N-CNTs-2	48 mV at 10 mA cm^{-2}	33	ACS Sustainable Chem. Eng., 2020, 8, 9136−9144.
CoRu-O/A@HNC-2	85 mV at 10 mA cm^{-2}	72.5	ACS Appl. Mater. Interfaces, 2020, 12, 51437−51447.
Ru−OC60-300/KB	4.6 mV at 10 mA cm^{-2}	24.7	ACS Catal., 2023, 13, 7597−7605.
Ru/rGO-700	26 mV at 10 mA cm^{-2}	71	Adv. Funct. Mater.,

			2021, 31, 2100698.
Ru-CoP/CC-2	45 mV at 10 mA cm^{-2}	98	ChemElectroChem., 2022, 9, e202101482.
Ru1CoP/CDs-1000	51 mV at 10 mA cm^{-2}	73.4	Angew. Chem. Int. Ed., 2021, 60, 7234-7244.
Ru-CB[6]/rGO	48 mV at 10 mA cm^{-2}	58.6	Chem. Commun., 2020, 56, 9392-9395.
M-Co@Ru/NC	34 mV at 10 mA cm^{-2}	55	Small., 2021, 17, e2105231.

Table S2. Summary of HER catalytic activities of Ru/HNC and some other catalysts reported in recent literatures (0.5 M H_2SO_4).

Catalysts	Overpotential	Tafel Slope (mV dec^{-1})	Ref.
Ru/HNC	**71** mV at 10 mA cm^{-2}	**52**	**In this work**
$Pt_{0.095}$-Ru_2P@Ru/CNT	27 mV at 10 mA cm^{-2}	20	ACS Sustainable Chem. Eng., 2021, 9, 15063–15071.
h-RuNS	154 mV at 10 mA cm^{-2}	102	ACS Appl. Nano Mater., 2021,4, 8530-8538.
Ru/CoxP@NC	165 mV at 10 mA cm^{-2}	55	ACS Sustainable Chem. Eng., 2019, 7, 9737-9742.
Ru/Ni_2P@NPC	89 mV at 10 mA cm^{-2}	62	ACS Sustainable Chem. Eng., 2019,7,17714-17722.
Ru@Co/N-CNTs	92 mV at 10 mA cm^{-2}	53	ACS Sustainable Chem. Eng., 2020, 8, 9136–9144.
Rh–Rh_2P@C	24 mV at 10 mA cm^{-2}	36	J. Mater. Chem. A, 2020, 8, 12378-12384.
Pt_1Ru_1/NMHCS-A	22 mV at 10 mA cm^{-2}	38	ACS Catal., 2022, 12, 5540-5548.
Ru_1CoP/CDs	49 mV at 10 mA cm^{-2}	52	Angew. Chem. Int. Ed., 2021, 60, 7234-7244.
RuSA-N-S-Ti_3C_2Tx	76 mV at 10 mA cm^{-2}	90	Adv. Mater., 2019, 31, 1903841.

A-Pt	18.8 mV at 10 mA cm^{-2}	27.8	ACS Appl. Mater. Interfaces, 2021, 13, 44224–44233.
Ru-N/BC	79 mV at 10 mA cm^{-2}	62	J. Mater. Chem. A, 2020, 8, 16669-16675.
h-RuNP	29 mV at 10 mA cm^{-2}	33	ACS Appl. Nano Mater., 2021, 4, 8530−8538.
Ru/MoO2	107 mV at 10 mA cm^{-2}	186	ACS Appl. Nano Mater., 2023, 6, 13926−13934.
Ru-CoP/NC	98 mV at 10 mA cm^{-2}	56	ACS Appl. Mater. Interfaces, 2021, 13, 56035−56044.
Ru@Co/N-CNTs-2	92 mV at 10 mA cm^{-2}	45	ACS Sustainable Chem. Eng., 2020, 8, 9136−9144.
Ru/RuS2	45 mV at 10 mA cm^{-2}	/	Angew. Chem., 2021, 133, 12436.
Ru/Ni2P	89 mV at 10 mA cm^{-2}	62	ACS Sustainable Chem. Eng., 2019, 7, 17714-17722.
2D-MoO2/Ru/NC	68 mV at 10 mA cm^{-2}	46	J. Phys. Chem. C, 2020, 124, 10804-10814.
Ru-Cu-MoO2	48 mV at 10 mA cm^{-2}	69	J. Mater. Chem. A, 2022, 10, 12341-12349.